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6. AUTHOR(S)
Phillip Jenkins[1], David Scheiman[1], Chris Goodbody[2], Carsten Baur[3], Paul Sharps[4],

Mitsuru Imaizumi[5], Henry Yoo[6], Ted Sahlstrom[7], Robert Walters[8], Justin Lorentzen[9], John Nocerino[10], Osman Khan[11], Robert Cravens[11], Jaun Valles[11], Chantal Toporow[12], Trinidad Gomez[13], Loreto Pazos Bazán[13], Sheila Bailey[14]

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[1]Ohio Aerospace Institute
[2]QinetiQ, Cody Technology Park
[3]Fraunhofer Institute for Solar Energy Systems, Freiburg, Germany
[4]Emcore Corporation, Albuquerque, NM
[5]JAXA Tsukuba Space Center, Tsukuba, Japan

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[6]Air Force Research Laboratory, Kirtland AFB, NM
[7]Dynacs Inc
[8]U.S. Naval Research Laboratory, Washington, DC
[9]SFA Inc.
[10]The Aerospace Corp, Los Angeles, CA
[11]Spectrolab Corporation, Sylmar, CA
[12]Northrop Grumman
[13]INTA-SPASOLAB, Madrid, Spain
[14]NASA Glenn Research Center

14. ABSTRACT
This paper reports the results of an international measurement round robin of monolithic, triple-junction, GaInP/GaAs/Ge space solar cells. Eight laboratories representing national labs, solar cell vendors and space solar cell consumers, measured cells using in-house reference cells and compared those results to measurements made where each lab used the same set of reference cells. The results show that most of the discrepancy between laboratories is likely due to the quality of the standard cells rather than the measurement system or solar simulator used.

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RESULTS FROM AN INTERNATIONAL MEASUREMENT ROUND ROBIN OF III-V TRIPLE-JUNCTION SOLAR CELLS UNDER AIR MASS ZERO

Phillip Jenkins[1], David Scheiman[1], Chris Goodbody[2], Carsten Baur[3], Paul Sharps[4], Mitsuru Imaizumi[5], Henry Yoo[6], Ted Sahlstrom[7], Robert Walters[8], Justin Lorentzen[9], John Nocerino[10], Osman Khan[11], Robert Cravens[11], Juan Valles[11], Chantal Toporow[12], Trinidad Gómez[13], Loreto Pazos Bazán[13] Sheila Bailey[14] [1]Ohio Aerospace Institute, [2]QinetiQ, Cody Technology Park, [3]Fraunhofer Institute for Solar Energy Systems, [4]Emcore Corporation, [5]JAXA Tsukuba Space Center, [6]Air Force Research Laboratory/VSSV, [7]Dynacs Inc.[8]U.S. Naval Research Laboratory, [9]SFA Inc., [10]The Aerospace Corporation [11]Spectrolab, [12]Northrop Grumman, [13]INTA-SPASOLAB, [14]NASA Glenn Research Center

ABSTRACT

This paper reports the results of an international measurement round robin of monolithic, triple-junction, GaInP/GaAs/Ge space solar cells. Eight laboratories representing national labs, solar cell vendors and space solar cell consumers, measured cells using in-house reference cells and compared those results to measurements made where each lab used the same set of reference cells. The results show that most of the discrepancy between laboratories is likely due to the quality of the standard cells rather than the measurement system or solar simulator used.

INTRODUCTION

Accurate performance characterization of solar cells for space applications is critical to the success of satellite missions. Any error in estimating the on-orbit performance of the solar array is magnified by the tremendous overhead associated with launch costs and performance limitations. The current generation of state-of-the-art space solar cells based on the GaInP/GaAs/Ge monolithically stacked, series connected, triple-junction solar cell, are complex devices and require sophisticated solar simulators to accurately characterize the cells. The space solar cell community considers this a serious enough problem that it has organized a technical working group to create standard calibration and measurement procedures for solar cells under the authority of the International Organization for Standardization (ISO).

The technical working group known as the AM0 Calibration Workshop, has conducted several measurement and calibration round robin activities using single junction silicon and GaAs solar cells [i,ii]. Recently, the working group published results from the first calibration round robin of multi-junction solar cells [iii]. The calibration round robin was limited to the NASA Jet Propulsion Laboratory (JPL), NASA Glenn Research Center (GRC) and Centre National d'Etudes Spatiales (CNES) as they are the only labs capable of calibrating monolithic triple-junction cells under AM0 conditions. Subsequent to the calibration round robin, a measurement round robin of the same cells was conducted. The measurement round robin is the subject of this paper.

Often times a laboratory will receive solar cells where there is no prior history and no matching standard cell(s) to set up the solar simulator. In these cases a laboratory makes its best effort based on their knowledge of the cell's spectral response, and whatever techniques they have established to set up the solar simulator and acquire I-V curves. Modern triple-junction GaInP/GaAs/Ge solar cells are particularly confounding due to their sensitivity to solar spectral distribution. Eight laboratories representing national labs, solar cell manufacturers and consumers of space solar cells, conducted a measurement round robin of III-V space solar cells.

METHODOLOGY

The working group thought it would be instructive to compare the results of a round robin where each lab would receive just a single triple-junction cell and make their best effort to measure its AM0 I-V curve and compare that to measurements where each lab used the same set of standard cells. In the first case, the cell measured was supplied without the AM0 calibration short circuit current value or any standard cells for setting up a solar simulator. Each lab could only rely on their existing standard cells and calibration methods. This simulates a "worst case" inter-comparison between labs where no common standard exists. In addition, a round robin measurement was conducted on a second cell where calibrated component cells were provided. Each lab measured the triple-junction cell using the supplied calibrated component cells to adjust their solar simulator intensity and spectrum. This represents a "best case" inter-comparison scenario. By using these two different measurement experiments, systemic problems such as solar simulator fidelity or electrical probing can be isolated from problems associated with individual reference cells and their use.

Cell Description

The Emcore Corporation supplied the solar cells used in this round robin. They are monolithic, series connected, GaInP/GaAs/Ge solar cells without built in bypass diodes. The cells were designed for optimized end of life performance in space and therefore current limited by the top GaInP cell to accommodate performance degradation in the GaAs and Ge cells during a mission in a radiation damaging environment. Emcore also provided matching component cells with similar spectral characteristics as the monolithic cells. The cells were mounted at NASA Glenn Research Center, in rugged holders designed to be compatible with the mounting requirements of all current AM0 calibration methods [iv]. The cells were calibrated using NASA Glenn's Lear jet facility, and the JPL and CNES balloons. The results of those calibrations, details of the cell holder and the spectral response of the cells are included in reference [3]. The cell holders have three different temperature sensor embedded in them; a copper-constantan (type-T) thermocouple, a 100 Ohm, three wire connected, RTD and an Analog Devices AD590 sensor. It was each lab's responsibility to use the temperature sensors as appropriate to measure the cell response at 25°C. The variety of solar simulators used by the labs included single source xenon arc, multi-source using xenon arc and filtered tungsten lamps or filters on a single source simulator to adjust the red/blue content.

Logistics

The schedule for measuring the cells was set up so that each lab would first measure the solar cell provided *without* supplied calibrated standards and report the result, before receiving the second cell supplied with calibrated standards. The cells were measured under standardized conditions at NASA Glenn Research Center before and after the cells were circulated to the laboratories to track any changes in cell performance. Aerospace Corporation's measurement of the cell circulated without standards was considered invalid due to damage to the cell incurred during shipping or handling. Each lab sent their results to a third party (QinetiQ) who compiled the results for this paper.

Reporting Conditions

Each lab was instructed to report short circuit current (Isc), open circuit voltage (Voc), fill factor (FF), the current (Imax) and voltage (Vmax) at maximum power under Air Mass Zero at 25°C.

Participants

Eight laboratories participated in the round robin:
Emcore Corporation, Albuquerque, New Mexico
Air Force Research Laboratory, Albuquerque, New Mexico
Spectrolab Corporation, Sylmar, California
JAXA, Tsukuba, Japan
Fraunhofer-ISE, Freiburg, Germany
SPASOLAB, Madrid, Spain
Naval Research Laboratory, Washington, DC
Aerospace Corporation, Los Angeles, California

RESULTS

The complied results for the cell measured without matched reference cells are shown in Table 1. JAXA reported results using two different simulators, a multi-source (JAXA 1) and a single source (JAXA 2). The values for various measurement parameters are normalized to the mean value of *all* data for each cell. For comparison, the results from the calibration round robin using balloon and Lear jet methods are included [3].

Laboratory	Isc	Voc	Imax	Vmax	Pmax	FF
Fraunhofer	97.9	100.1	97.9	100.2	98.1	100.1
Emcore	100.0	99.7	100.0	99.7	99.7	100.1
AFRL	106.2	100.2	106.3	99.5	105.7	99.3
Spasolab	98.5	99.5	97.9	99.4	97.3	99.3
JAXA 1	99.3	100.4	99.5	100.5	100.0	100.5
JAXA 2	99.2	100.3	99.0	101.0	100.0	100.4
Spectrolab	98.6	100.0	98.8	100.5	99.3	100.5
NRL	103.2	100.2	103.9	99.3	103.2	99.6
CNES	98.5	99.7	98.2	99.9	98.1	99.9
NASA GRC	98.5	100.3	98.1	101.3	99.3	100.8
JPL	100.0	99.8	100.3	98.9	99.2	99.4
Standard Deviation	**2.5**	**0.3**	**2.7**	**0.8**	**2.4**	**0.5**

Table 1. Measured values for a triple-junction cell measured using only in-house reference cells.

Table 2 shows the results for the second cell, measured with the benefit of matched, calibrated [v], component reference cells mounted in exactly the same manner as the test cell.

Laboratory	Isc	Voc	Imax	Vmax	Pmax	FF
Fraunhofer	100.2	100.0	100.2	100.2	100.4	100.3
Emcore	99.8	99.6	99.7	98.4	98.1	98.8
AFRL	99.8	100.2	99.7	100.4	100.1	100.0
Spasolab	100.5	99.8	100.0	99.5	99.4	99.3
JAXA 1	100.0	99.9	100.2	100.1	100.3	100.5
JAXA 2	100.0	100.0	100.0	100.7	100.7	100.8
Spectrolab	100.0	99.8	99.8	100.7	100.5	100.4
NRL	99.7	100.5	99.9	100.7	100.6	100.4
Aerospace	100.0	100.2	100.4	99.2	99.6	99.4
Standard Deviation	**0.2**	**0.3**	**0.2**	**0.8**	**0.8**	**0.7**

Table 2. Measured values for a triple-junction cell where each laboratory used the same reference cells.

Looking first at Isc, the cell measured without matched standards (Table 1), shows a relatively tight grouping with only one or two outliers. It is interesting to note, that if one computes the average Isc value from just the measurement laboratories and compare that to the average value from just the calibration methods (NASA GRC, JPL and CNES [3]) the difference is 1.3%.

Considering the diversity of methods, simulators and standard cells, this is remarkably good agreement.
The voltage parameters, Voc and Vmax, have significantly lower deviation than the current measurements. Predictably, the Pmax uncertainty (comparing standard deviation) is closer to the Isc and Imax values than the voltage values. Insight into the cause of the larger Isc discrepancy can be gained from the results of the second cell measured (Table 2) where all labs used the same spectrally matched reference cells.

The deviation in the measured Isc values in Table 2 are an order of magnitude lower than without the benefit of matched standards. Furthermore, the voltage measurements have nearly identical uncertainties compared to the cell in Table 1. This indicates that the uncertainties in the voltage measurements are substantially decoupled from the uncertainty in the current measurement. This is not surprising since the cell voltage is related only to the current by a log function. It also indicates that all of the labs have high enough fidelity in their measurement systems, to accurately measure triple-junction solar cell I-V curves given the proper standard cells.

The JAXA results illustrate this point well. The JAXA 1 and JAXA 2 results are nearly identical in spite of the fact that the JAXA 1 results are based on a multi-source simulator and the JAXA 2 results are from a single source simulator. This is likely due to the fact that these cells are top cell current limited and therefore behave much like a single junction cell. However, it remains to be seen if this result will hold up for cells that are not top cell limited, such is the case in radiation damaged multi-junction cells. The AM0 Workshop group is currently organizing a new measurement round robin based on measuring radiation damaged cells.

Interestingly, the significant outliers for Isc and Imax in Table 1 are biased towards higher values. One possible explanation for this is that the in-house standards used to set up the solar simulators are damaged. Typically, as a standard cell degrades it will lose short circuit current. If the solar simulator is set up so that its output drives the standard cell at its presumed calibration value, the intensity of the simulator will be too high and bias the measurement of solar cells above their true value.

CONCLUSION

This effort is the fourth round robin activity conducted by the AMO Calibration Workshop. Having each lab measure a cell with and without the same standard cells gave insight into the likely cause of uncertainty. This exercise shows that the underlying problem was related more with not having a proper standard cell rather than any systemic problem within a lab. The AM0 Workshop is currently planning a new round robin activity measuring radiation damaged triple-junction solar cells.

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[iv] ISO/CD 15387 “Space Systems – Space Single Junction Solar Cells – Measurement and Calibration Procedures.”

[v] The calibration values for the component reference cells were determined using NASA GRC High Altitude Aircraft calibration.